Estimating solar ultraviolet irradiance (290-385 nm) by means of the spectral parametric models: SPCTRAL2 and SMARTS2

I. Foyo-Moreno, J. Vida, F. J. Olmo, L. Alados-Arboledas

Ann. Geophysicae 18, 1382–1389 (2000) © EGS – Springer-Verlag 2000

Annales Geophysicae

Estimating solar ultraviolet irradiance (290–385 nm) by means of the spectral parametric models: SPCTRAL2 and SMARTS2

I. Foyo-Moreno, J. Vida, F. J. Olmo, L. Alados-Arboledas

Departamento de Física Aplicada, Universidad de Granada, 18071-Granada, Spain

Received: 10 November 1999 / Revised: 5 July 2000 / Accepted: 7 July 2000

Abstract. Since the discovery of the ozone depletion in Antarctic and the globally declining trend of stratospheric ozone concentration, public and scientific concern has been raised in the last decades. A very important consequence of this fact is the increased broadband and spectral UV radiation in the environment and the biological effects and heath risks that may take place in the near future. The absence of widespread measurements of this radiometric flux has lead to the development and use of alternative estimation procedures such as the parametric approaches. Parametric models compute the radiant energy using available atmospheric parameters. Some parametric models compute the global solar irradiance at surface level by addition of its direct beam and diffuse components. In the present work, we have developed a comparison between two cloudless sky parametrization schemes. Both methods provide an estimation of the solar spectral irradiance that can be integrated spectrally within the limits of interest. For this test we have used data recorded in a radiometric station located at Granada (37.180°N, 3.580°W, 660 m a.m.s.l.), an inland location. The database includes hourly values of the relevant variables covering the years 1994–95. The performance of the models has been tested in relation to their predictive capability of global solar irradiance in the UV range (290–385 nm). After our study, it appears that information concerning the aerosol radiative effects is fundamental in order to obtain a good estimation. The original version of SPCTRAL2 provides estimates of the experimental values with negligible mean bias deviation. This suggests not only the appropriateness of the model but also the convenience of the aerosol features fixed in it to Granada conditions. SMARTS2 model offers increased flexibility concerning the selection of different aerosol models included in the code and provides the best results when the selected models are those considered as urban. Although SMARTS2 provide slightly worse results, both models give estimates of solar ultraviolet irradiance with mean bias deviation below 5%, and root mean square deviation close to experimental errors.

Key words: Atmospheric composition and structure (transmission and scattering of radiation) – Meteorology and atmospheric dynamics (radiative process)

Correspondence to: L. Alados-Arboledas
e-mail: alados@ugr.es

1 Introduction

The great importance of ultraviolet solar radiation, is well known to have serious implications for the biosphere, including human health (Horneck, 1995). This fact justifies the growing interest on this radiative flux during the two last decades. The increase of ultraviolet radiation has been widely discussed due to the decrease of stratospheric ozone and the consequent risks for living organisms. In spite of the world concern about the UV problem, few radiometric stations measure systematically and continuously this radiometric magnitude. This makes it necessary to use the more or less sophisticated models that provide estimation of the energy arriving at the Earth's surface in this band of the spectrum. However, recent efforts to implement radiometric networks will help fill this gap. This includes ground-based instruments to determine the surface flux of UV radiation and its long-term changes over the United States implemented jointly by a number of US government agencies (EOS, 1999). In addition, in the frame of the Second European Stratospheric Arctic and Mid-latitude Experiment, an intensive program of spectral measurements of global solar UV radiation was organized at several European sites (Bais *et al.*, 1997). However, only the use of models can fill in the broad areas over land where there is no instrumentation and most areas over the Earth's oceans.

This work is devoted to the study of parametric models that provide an estimate of the solar ultraviolet radiation under cloudless conditions. This cloudless sky estimation, combined with the appropriate algorithm that takes into account the cloud effect, provides an estimation of solar ultraviolet radiation by means of surface cloud observation or remote sensing data. This is when one uses cloud observations registered by surface observers or radiances measured from remote sensing platforms such as geostationary satellites. We consider spectral models, which are physically based. These models use spectral transmittances of the extinction process that takes place in the atmosphere, obtained by a parametric approach. They estimate the UV radiation under cloudless skies, when the solar radiation reaching the Earth's surface presents the highest values. This information is rather interesting for the radiative effect. The flux under cloudless conditions can be used to obtain the maximum energy that a given system could receive in a given location, which in turn determines the maximum radiative effect over biological or non-biological systems. In particular, the high frequency of cloudless conditions in the Mediterranean area is responsible for the greater levels of UV radiation received at these locations in comparison with other places at comparable latitudes in the Northern Hemisphere (Bais *et al.*, 1993).

When solar radiation propagates through the Earth's atmosphere it is attenuated by scattering (due to air molecules and aerosols) and absorption processes (mainly by ozone, water vapor, oxygen, carbon dioxide and absorbing aerosols such as dust and smoke). The absorption occurs in lines and bands, while the scattering takes place over the whole solar spectrum, with more or less spectral dependence depending on the aerosols characteristics. The phenomena are complex since those factors that control the attenuation of solar radiation can change from one place to another or vary as a function of time.

In this work, we will only consider the real atmosphere with cloudless sky, and only models aimed at the computation of clear sky irradiances on a horizontal surface are considered here. In a previous study (Foyo-Moreno *et al.*, 1993) the importance of a correct modeling of clear sky irradiances to obtain a good estimate under all sky conditions was shown. This can be achieved by using a combination of an appropriate clear sky model with appropriate cloud transmission functions. Additionally, the global evaluation of the solar irradiance over extended areas by means of satellite data, requires an appropriate but simple model in order to provide the cloudless sky value of the estimation algorithm (Olmo *et al.*, 1996).

The models considered are SPCTRAL2 (Bird and Riordan, 1986) and SMARTS2 (Gueymard, 1995). Both models use a parametrization of the radiative processes of the atmosphere and provide an estimation of the spectral solar irradiance in the complete solar spectrum. In the corresponding section, we will show the models main features and we will emphasize their more relevant differences.

2 Model description

2.1 The SPCTRAL2 model

The SPCTRAL2 model analyzed in our study corresponds to the spectral model proposed by Bird and Riordan (1986). The original model (Bird, 1984) is based on previous parametric models developed by Leckner (1978) and by Brine and Iqbal (1983). Justus and Paris (1985) and Bird and Riordan (1986) have made improvements to the simple model approached by Bird (1984) including refinements based on comparisons with results of rigorous radiative transfer and with measured spectra.

The model uses the extraterrestrial spectral irradiance obtained by Fröhlich and Wehrli (Private Communication 1981) of the World Radiation Center, with a 10 nm resolution for 122 wavelengths in the range 300 nm to 4000 nm. Detailed equations used in the model formulation can be found in Bird and Riordan (1986). In order to cover the spectral range of our radiometer, 290–385 nm, we have included the spectral data needed. Thus, solar extraterrestrial spectral irradiance and ozone absorption coefficients, following the World Radiometric Center Spectrum (Fröhlich and Wehrli, Private Communication 1981) and Vigroux's (1953) coefficients as included in Iqbal (1983) have been added. The Vigroux (1953) cross sections for ozone are slightly greater than more recent determination such as those used in SMARTS2 code (Gueymard, 1995). An error analysis performed on this subject suggests that in the range 295–385 nm the error in ozone transmittance associated to the use of Vigroux (1953) cross section can reach a value of about 1%, for the worst combination of optical air mass and total column ozone. For 290 nm the magnitude of this maximum is close to 3%. Varotsos (1994) used a similar model in his analysis of ultraviolet solar radiation measured with TUVR at Athens, Greece, concluding the close agreement of simulated and measured values.

The required input parameters are local geographic coordinates, atmospheric pressure, precipitable atmospheric water vapor and aerosol information. The aerosol information required by the model is the aerosol optical depth at 500 nm, the model uses fixed values for the remaining optical features of the aerosol such as Angstrom's exponent α or the single scattering albedo. In this sense, we can say that the model includes its own aerosol model. Table 1 presents these values, where F_c is forward scattering, α is Angstrom's exponent, g is the aerosol asymmetry factor, ω_0 is aerosol single scattering albedo, $\omega_{0.4}$ is single scattering albedo at 0.4 μm, ω' is the wavelength variation factor and ρ is the ground albedo.

Table 1. Values for the characteristic parameters of the model SPCTRAL2

F_c	α	g	ω_0	$\omega_{0.4}$	ω'	ρ
0.81	1.14	0.65	0.57	0.945	0.095	0.15

The SPCTRAL2 code includes some modifications proposed by Bird and Riordan (1986) in order to reduce the overestimation in the visible and ultraviolet spectral ranges. This changes affect the diffuse component and through this the global component, the radiometric flux analyzed in this study.

2.2 The SMARTS2 model

The model SMARTS2 (Simple Model of the Atmospheric Radiative Transfer of Sunshine) was first proposed by Gueymard (1993), being the last version the result of a series of additional improvements (Gueymard, 1995).

The model calculates the direct beam and diffuse radiation components considering the separate parametrization of the various extinction processes affecting the transfer of short-wave radiation in a cloudless atmosphere. The solar extraterrestrial spectrum used in the model covers the wavelength range between 280 nm and 4020 nm with a resolution of 1 nm. In its last Revised Version, the model includes very accurate absorption coefficients derived from spectroscopic data (Gueymard, 1998). The model permits the consideration of different aerosol models (standard models and models depending on the relative humidity) or the choice of a particular model defined by the user.

As indicated there are nine aerosol models available in SMARTS2. There are two models proposed by Braslau and Dave (1973), B&DC (aerosol type C) and B&DC1 (aerosol type L). Additionally, there are four models proposed by Shettle and Fenn (1979) that depend on the relative humidity: MAR (maritime), RUR (rural), URB (urban) and TRO (tropospheric). Finally, the last three models correspond to standard atmospheres (SRA, WMO, 1986), SCONT (continental), SMARIT (maritime) and SURBAN (urban).

The estimation of atmospheric turbidity has been carried out from available broadband radiation following the procedure developed by Gueymard (1998). This method is especially interesting because the four widely used turbidity coefficients (Angström, Linke, Schüepp and Unsworth-Monteith) can be easily interrelated without the use of any empirical relation. Gueymard (1998) has shown that the Unsworth-Monteith coefficient slightly depends on both zenith angle and water vapor, the Linke coefficient slightly depends on zenith angle but considerably on water vapor and the Angström and Schüepp depend only on aerosol. In this way, the data concerning the turbidity information are introduced by means of the Schuepp's turbidity coefficient (at 0.5 μm) although the model permits different possibilities. Thus, the user can choose among the aerosol optical thickness at 0.5 μm, Angstrom's turbidity coefficient (at 1 μm), meteorological range or prevailing visibility as observed at airports. The aerosol models include two average values of Angstrom's wavelength exponent: α_1 and α_2, for wavebands separated by 0.5 μm, respectively, thus Angstrom's exponent α is the average value.

Table 2 presents the values for the characteristics parameters of the three standard aerosol models and the two models from Braslau and Dave (1970). Several of these values correspond to average values while others are the fixed values included in the models. All these models consider the Angstrom's wavelength exponents (α_1 and α_2) and the corresponding α as fixed values. For the standard models, the aerosol single scattering albedo (ω_0) and the aerosol asymmetry factor (g) present a dependency with the wavelength in the form:

$$\omega_0 = A_0 + A_1\lambda + A_2\lambda^2 + A_3\lambda^3 \tag{1}$$

$$g = B_0 + B_1\lambda + B_2\lambda^2 + B_3\lambda^3 + B_4\lambda^4 \tag{2}$$

where the coefficients are fixed values which differ according to the considered model. The model of Braslau and Dave (1973) assigns a fixed value to ω_o but the version B&DC1 includes a wavelength dependency different to that of the standard models. Finally, both models assign a fixed value for g.

The models depending on humidity consider the parameters α_1, α_2 and consequently α variables, that is as functions of the relative humidity. On the other hand, ω_0 and g depend on both the relative humidity and the wavelength. The dependency on wavelength is calculated through Eqs. (1) and (2), but with coefficients depending on the relative humidity. Table 3 shows the minimum and maximum values and the averages values

Table 2. Values for the characteristic parameters for the standard models and Braslau and Dave's (1973) model included in SMARTS2

Model	α_1	α_2	α	ω_0	g
B&DC	−0.311	0.265	−0.023	1.0	0.8042
B&DC1	−0.311	0.265	−0.023	0.9	0.8042
SMARIT	0.283	0.265	0.274	0.6	0.7471
SCONT	0.940	1.335	1.138	0.6	0.6541
SURBAN	1.047	1.472	1.260	0.6	0.6085

Table 3. As Table 2 but for the models depending on the relative humidity

Model	α_1 [min, max]	Mean	α_2 [min, max]	Mean	α [min, max]	Mean	ω_o [min, max]	Mean	g [min, max]	Mean
MAR	0.15,0.50	0.43 ± 0.06	0.05,0.65	0.57 ± 0.09	0.10,0.06	0.50 ± 0.08	0.98,1.00	0.979 ± 0.004	0.69,0.82	0.71 ± 0.02
RUR	0.70,0.95	0.93 ± 0.02	1.15,1.45	1.43 ± 0.02	0.93,1.20	1.18 ± 0.02	0.98,1.00	0.60 ± 0.04	0.67,0.78	0.68 ± 0.02
URB	0.50,0.85	0.83 ± 0.02	1.14,1.20	1.18 ± 0.03	0.85,1.05	1.01 ± 0.01	0.65,1.00	0.67 ± 0.04	0.70,0.80	0.71 ± 0.02
TRO	0.75,1.03	1.01 ± 0.02	1.90,2.40	2.37 ± 0.05	1.30,1.70	1.69 ± 0.04	0.98,1.00	0.60 ± 0.04	0.66,0.78	0.67 ± 0.02

of these parameters. The dependency of the coefficients α_1 and α_2 with the relative humidity is:

$$\alpha_1 = \frac{C_1 + C_2 X}{1 + C_3 X} \tag{3}$$

$$\alpha_2 = \frac{D_1 + D_2 X + D_3 X^2}{1 + D_4 X} \tag{4}$$

where X is:

$$X = \cos(0.9U\pi/180) \tag{5}$$

and U is the relative humidity.

Therefore, among others, the main difference between SMARTS2 and SPCTRAL2 models, is the capability of the former to select the aerosol model from a set of built in models.

A common feature of both models in order to estimate UV global irradiance are the required input data regarding ozone and aerosol characteristics. The total ozone data have been provided by the Spanish INTA (National Institute of Aerospatial Technique) using the Dobson system. The precision of the Dobson instrument for measuring ozone ranges from 2 to 5%. The maximum error value of a 5% in the ozone data, introduces an error in the output of the SPCTRAL2 and SMARTS2 models of 0.4 and 0.3% respectively. The aerosol information has been introduced by means of the turbidity coefficient β, with associated errors up to a 10%. This maximum error implies a relative error in the models output of a 1.5% in SPCTRAL2 and a 2.4% in SMARTS2.

3 Data description and experimental device

The data set was obtained in a radiometric station installed at Granada, an inland location in southeastern Spain. The measurements cover two years: 1994 and 1995. The data are registered as one mean minute values and from these data hourly values have been generated.

Granada is a medium-size city, characterized by a continental climate having a rather wide temperature range, with cool winters and hot summers. The diurnal temperature range allows freezing to occur on winter nights. Most rainfall occur during spring and wintertime. Summer is normally very dry with little rainfall in July and August. Granada also presents a low humidity regime.

Broadband solar irradiance (0.3–3 μm) including global and diffuse components were continually recorded by means of two Kipp and Zonen model CM-11 pyranometers. For diffuse measurements the second pyranometer uses a polar axis shadowband to measure the diffuse component that is corrected following the method proposed by Batlles *et al.* (1995). Ultraviolet global irradiance (290–385 nm) on a horizontal surface was measured by means of an Eppley TUVR radiometer. The calibration constant of the radiometer has been checked every year against a well calibrated spectroradiometer (LI-1800, LI-COR), detecting a 2% degradation per year. More details about the calibration's constant checking and experimental device characteristics, such as the thermal dependence and corresponding correction procedure, can be found in Foyo-Moreno *et al.* (1998). Considering the TUVR cosine response we have limited our study to solar zenith angles lower than 80°. Measurements of solar global and diffuse irradiance have an estimated experimental error of about 2–3%, while the TUVR radiometer has a relative error less than 5%.

Air temperature and relative humidity at 1.5 m are included among the registered meteorological variables. The water vapor content was estimated from dewpoint temperature (Won, 1977). The total column ozone values have been measured at El Arenosillo (Huelva, 37.1°N, 6.7°W) using the Dobson unit number 120 and have been kindly provided by INTA (Instituto Nacional de Técnica Aeroespacial). For our study we have used the monthly average values.

4 Model evaluations

4.1 SPCTRAL2

This simple parametric model computes broadband transmittance for the different atmospheric extinction processes. The use of these transmittances allows the computation of the direct beam component and the diffuse component, and the global irradiance is obtained by a combination of the horizontal projected direct irradiance and the diffuse horizontal irradiance.

The model has been evaluated at Granada. Table 4 shows the results obtained including determination coefficient r^2, slope b, and intercept a, of the linear regression of UV global irradiance estimated versus measured data. The determination coefficient gives an evaluation of the experimental data variance explained by the model. The model performance has been evaluated about its predictive capability using mean bias deviation (MBD) and root mean square deviation (RMSD) both as percentage of the mean experimental values. These statistics allow the detection of both the differences between experimental data and model estimates and the existence of systematic over-or underestimation tendencies. These statistical indicators are defined by:

$$\mathrm{MBE} = \frac{1}{N}\sum_{i=1}^{N} \frac{UV_{\mathrm{est},i} - UV_{\mathrm{meas},i}}{UV_{\mathrm{meas},i}} \tag{6}$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\frac{UV_{\mathrm{est},i} - UV_{\mathrm{meas},i}}{UV_{\mathrm{meas},i}}\right)^2\right]^{1/2} \tag{7}$$

Table 4. Statistical results concerning SPCTRAL2 model behavior

Locality	a	b	r^2	MBD (%)	RMSD (%)
Granada	0.56	0.98	0.99	0.5	6.7

in which UV_{est} and UV_{meas} are the estimated and measured values, respectively, and N is the number of data.

From Table 4, it can be seen that the results are very satisfactory, with a slope close to unity, indicating close agreement between the estimated values and the measured ones for the whole range of measurements. The overall performance is rather good with a slight overestimation approximately close to 1% and a RMSD close to 7%. We have checked the confidence level for the hypothesis that the experimental and the synthetic data set have means not significantly different by applying an ANOVA test to the data. Our results show that this confidence level is greater than 85%. Figure 1 shows the scatter plot of estimated versus measured values. The points are close to the perfect fit line 1:1, suggesting that appropriate estimates can be obtained for the whole range of experimental values. Nevertheless, separated analyses concerning the model bias indicate that there is a slight tendency to bias with the direct irradiance values. For low solar direct irradiance values, the model shows a slight systematic tendency to underestimation, while for solar direct irradiance values greater than 600 W/m^2 there is greater spread of the bias that shows an overall tendency to overestimation. Considering that in our case we have limited our analysis to cloudless conditions, this means a dependency on either aerosol load or optical air mass. Our analysis suggest that the bias does not show any special dependence with this last parameter, suggesting that the unique dependence shown for the model bias, although slight, is that of the aerosol load.

Recently Boscá *et al.* (1997) have proposed a modified version of the SPCTRAL2 code. Among other innovations, these authors propose the implementation of SPCTRAL2 using a set of aerosol models that have been described in Table 5. The models available are MRC (maritime-rural-clear), MR (mean rural), RU (rural-urban), MU (mean urban) and PU polluted urban. Utrillas *et al.* (1998) have checked the complete modified

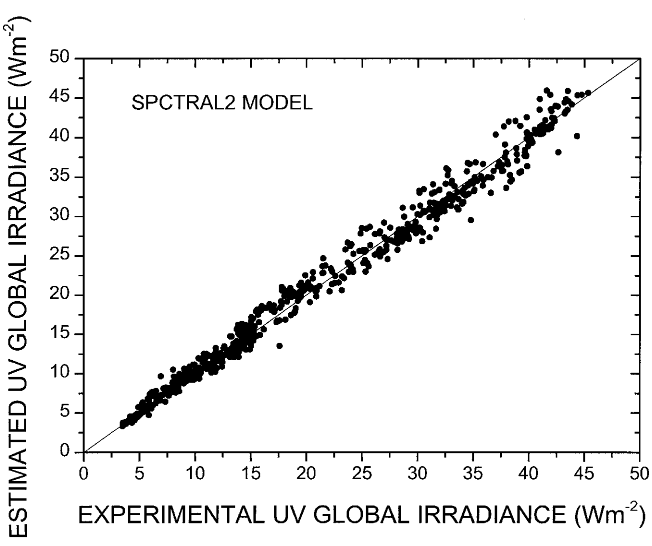

Fig. 1. Comparison of the UV global irradiance based on measurements and calculations using the SPCTRAL2 model

Table 5. As in Table 1, but considering the modifications suggested by Boscá *et al.* (1997)

Model	F_c	ω_0	$\omega_{0.4}$	α	g
MRC	0.78	0.94	0.96	1.4	0.60
MR	0.81	0.90	0.95	1.3	0.65
RU	0.84	0.81	0.64	1.3	0.70
PU	0.87	0.59	0.74	1.1	0.75

Table 6. Statistical results concerning SPCTRAL2 model behavior with the modifications of Boscá *et al.* (1997)

Model	a	b	r^2	MBD (%)	RMSD (%)
MRC	0.58	0.96	0.98	−4.1	8.9
MR	0.58	0.96	0.98	−4.2	9.1
RU	0.58	0.96	0.97	−8.2	13.0
MU	0.58	0.96	0.96	−9.5	14.5
PU	0.58	0.95	0.95	−12.9	18.1

version of this model with spectral data. In our study we have considered the convenience of introducing additional flexibility to the SPCTRAL2 code, allowing the selection among different aerosol models. Thus, the aerosol models described by Boscá *et al.* (1997) have been included as possible choices in the code.

Table 6 shows the results obtained for SPCTRAL2 code when run with the different aerosol models. We can appreciate that at Granada, all models underestimate with MBD oscillating between 4 and 13% and the RMSD ranging between 9 and 18%. The worst results correspond to the polluted urban model. On the other hand, The Maritime-Rural-Clear model and the Mean Rural provide similar results with MBD close to 4%. These results are slightly worse than those obtained with the built-in aerosol model included in the original version of the SPCTRAL2 code. In this sense, it is interesting to note that except for the coefficient α, the rest of the aerosol model parameters corresponding to MRC and MR are close to those fixed in the original version of SPCTRAL2 code. Concerning the value of Angstrom's exponent α it is interesting to note that in a recent study developed in our study area it was shown that the modal value for this exponent is about 1.14.

The general underestimation tendency that we obtain when SPCTRAL2 is used with the aerosol models included in Table 5 is encountered also by Utrillas *et al.* (1998). These authors have presented a comparative study of both SPCTRAL2 and SMARTS2 models, analyzing their predictive capability of spectral direct irradiance at Valencia, Spain. Their results indicate that the version of SPCTRAL2 code modified according to Boscá *et al.* (1997) provides estimates of the solar direct irradiance with MBD ranging between −3.1 and −10%, and the RMSD in the range 11–16%.

4.2 SMARTS2

As mentioned already, this model permits the choice among nine aerosol models. Three models correspond to the Standard Radiation Atmosphere (WMO, 1986). Four models depending on the relative humidity have been proposed by Shettle and Fen (1979), and, finally, two models have been proposed by Braslau and Dave (1973).

This code requires as input parameters the local geographical parameters (site's latitude and altitude). The code permits the introduction of ground meteorological data, although it allows the choice of 10 different reference atmospheres if this information is not available to the user.

The code calculates the total NO_2 absorption, without distinction between the tropospheric and stratospheric contributions. The total column abundance of NO_2 is calculated with a correction for site's altitude and considering a mean value from reference atmosphere, which is by default USA. The precipitable water can be determined by different methods, being possible to use climatological averages or empirical equations from surface data of temperature and humidity, we have used this last method. The assigned value for ground albedo is 0.15 following precedent studies (Alados *et al.*, 1999).

We have evaluated SMARTS2 at Granada using the different aerosol models. Table 7 shows the results obtained including the statistical parameters mentioned. From Table 7 and through a graphic analysis of estimated versus measured data, we have detected a noticeable and systematic overestimation for all the aerosol models, excluding the urban aerosol models. These last models show the lowest overestimation, which is in the range 2–4%. As a general feature, all the models present slopes that differ from unity from 10 to 17%, with the urban models having the best fit. The lowest RMSD correspond to the urban models. Thus, we may conclude that SMARTS2 provides estimations of the solar global ultraviolet radiation with systematic deviation, within the experimental error, if the urban aerosol models are selected. The lowest MBD is obtained when the selected model is SURBAN that presents a MBD close to 2%. Figure 2 shows the scatter plot of estimated versus measured values for this last model. The spread of the points around the perfect fit line 1:1 is in accordance with the RMSD and MBD values shown in Table 8. As in our study of SPCTRAL2 model, a separate analysis concerning the model bias has been performed. This analysis indicates that there is a correlation of this bias with the aerosol load. In the case of low aerosol loads the model shows a slight underestimation that first tends to zero and afterward shows a slight overestimation as the aerosol load increases. This dependence is also noticeable with the direct irradiance values, being in accordance with the negligible dependence of the bias with optical air mass. Thus, although in a different degree the bias provided by SMARTS2 with the SURBAN aerosol model follows a pattern similar to that shown by SPCTRAL2.

Table 7. Statistical results concerning SMARTS2 model behavior

Model	*a*	*b*	r^2	MBD (%)	RMSD (%)
B&DC	0.59	1.17	0.99	20.0	23.6
B&DC1	−0.07	1.16	0.99	15.8	19.5
SMARIT	0.41	1.17	0.99	18.6	22.0
SCONT	−0.33	1.15	0.99	13.0	16.9
SURBAN	−1.59	1.10	0.97	2.3	12.2
MAR	0.38	1.16	0.99	17.9	21.3
RUR	0.09	1.15	0.99	15.3	18.8
URB	−1.17	1.10	0.98	4.1	11.9
TRO	0.18	1.15	0.99	15.8	19.1

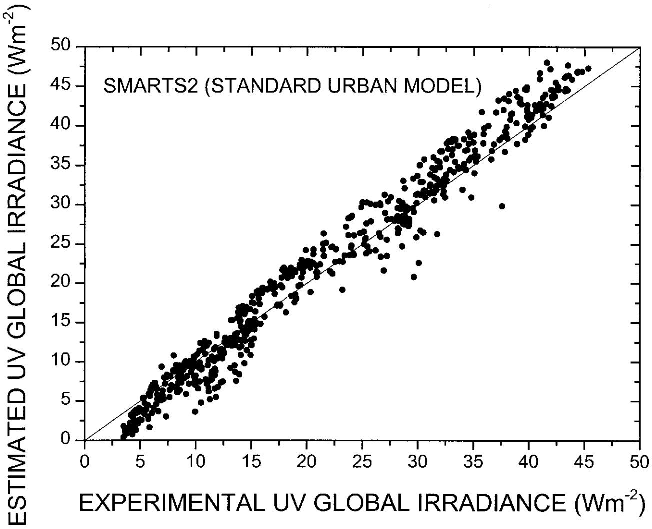

Fig. 2. Comparison of the UV global irradiance based on measurements and calculations using the SMARTS2 model (Standard Urban aerosols model)

5 Conclusions

In our study, we have tested two spectral parametric models with reference to their capability for predicting global ultraviolet irradiance (290–385 nm). Both models are developed by parametrizing the different radiative processes that affect the solar radiation as it passes through the atmosphere. Both parametrize separately the diffuse and direct solar irradiance computing the solar global irradiance by the appropriate addition of both components. Among other differences, the two models vary in their treatment of aerosols. Aerosols are responsible for both scattering and absorption of solar radiation. This combined extinction shows a characteristic spectral dependence that presents its greater contribution in the shorter wavelengths of the solar spectrum. Atmospheric aerosol is a very dynamic component of the atmospheric system, presenting great variation both in space and time. As our study focus in these wavelengths, aerosols are the more problematic atmospheric component for the correct estimation of ultraviolet solar radiation in the range 290–385 nm under cloudless conditions.

Our study has been conducted by checking the models against experimental data registered in an inland radiometric station located in southeastern Spain. The data set covers a two year period that ensures a variety of sky conditions, although we have been limited to cloudless skies.

In its original version, the SPCTRAL2 code does not allow the selection of different aerosol models, but the values of the aerosol parameter provide a good estimation of the experimental value. This points to convenience of this model and the validity of the included aerosol parameters for the Granada conditions. In fact, a later analysis of the model including the possibility of selecting various aerosol models different to those built in to the original version does not provide better results.

SMARTS2 code presents higher flexibility than SPCTRAL2 and allows the selection of different aerosol models and the use of standard models of the atmosphere, if in situ meteorological information is not available. In this sense, we have tested the model using available meteorological information and running it for the different aerosol model included in it. The best results correspond to the urban aerosol models, SURBAM being the one providing estimates closer to the experimental values. Although the results are slightly worse than those from SPCTRAL2, they are accurate enough, with MBD below the experimental errors.

The bias associated with SPCTRAL2 and SMARTS2 with the selection of the SURBAN model follows similar patterns. Their dependence on the solar direct irradiance values reveals a dependence on the aerosol load, considering the absence of any dependence on the optical air mass.

It may be concluded that both models provide appropriate estimation of the solar global ultraviolet radiation (290–385 nm). The flexibility of SMARTS2 with its built-in capability to select different aerosol models is a very convenient feature. Nevertheless, for our location the fixed values for the aerosol parameter included in SPCTRAL2 provides estimations that are more accurate. Additional work extending the test to other locations, using available data sets will provide a test for the other aerosol models included in SMARTS2 and it will confirm its potential general applicability.

Acknowledgements. This work was supported by La Dirección General de Ciencia y Tecnología from the Education and Research Spanish Ministry through the project CLI-98-0957. We are very grateful to the Armilla Air Base Meteorological Office Staff and specially to Guillermo Ballester Valor, Meteorologist Chief of the Meteorological Office for the maintenance of the radiometric devices. The Instituto Nacional de Meteorología kindly provided the cloud observation information. The ozone values required for both models have been kindly provided by INTA (Instituto Nacional de Técnica Aeroespacial). We thank Dr. Christian Gueymard for his help in providing the SMARTS2 code. L. Alados-Arboledas is an American Meteorological Society Member.

Topical Editor D. Murtagh thanks J. R. Herman for the help in evaluating this paper.

References

Alados, I., M. Pérez, F. J. Olmo, and L. Alados-Arboledas, Parametric modelling of photosynthetically active radiation in Spain. *Agric. Forest. Meteorol.* (accepted for publication), 1999.

Bais, A. F., C. S. Zerefo, C. Meleti, I. C. Ziomas, and K. Tourpali, Spectral measurements of solar UVB radiation and its relations to total ozone, SO_3, and clouds, *J. Geophys. Res.*, **98,** 5199–5204, 1993.

Bais, A. F., M. Blumthaler, A. R. Webb, J. Groebner, P. J. Kirsch, B. G. Gardiner, C. S. Zerefos, F. Svenoe, and T. J. Martin, Spectral UV measurements over Europe within the Second European Stratospheric Arctic and Midlatitude Experiment activities, *J. Geophys. Res.*, **102,** 8731–8736, 1997.

Batlles, F. J., F. J. Olmo, and L. Alados-Arboledas, On shadowband correction methods for diffuse irradiance measurements, *Sol. Energy*, **54,** 105–114, 1995.

Bird, R. E., A simple spectral model for direct normal and diffuse horizontal irradiance, *Sol. Energy*, **32,** 461–471, 1984.

Bird, E. R., and C. Riordan, Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted palnes at the Earth's surface for cloudless atmospheres, *J. Clim. Appl. Meteorol.*, **25,** 87–97, 1986.

Boscá, J. V., J. M. Pinazo, and J. Cañada, Modificación del programa SPCTRAL2 para la estimación de irradiancias solares espectrales directa, difusa y global a partir de unas mínimas medidas experimentales, in *Proccedings of VIII Congreso Ibérico de Energía Solar*, SPESISES, Eds. de Oliveira Fernandes E., E. Maldonado, and M. Gueldes, Porto, Portugal, 111–115 (in Spanish), 1997.

Braslau, N., and J. V. Dave, Effects of aerosols on the transfer of solar energy through realistic model atmospheres, *J. Appl. Meteorol.*, **30,** 601–619, 1973.

Brine, D. T., and M. Iqbal, Solar spectral diffuse irradiance under cloudless skies, *Sol. Energy*, **30,** 447–453, 1983.

EOS, Transactions, American Geophysical Union, US Interagency UV Monitoring Program established and operating, **80**(10), 113–116, 1999.

Foyo-Moreno I., L. Alados-Arboledas, and Y. Castro-Díez, Parametrizing cloud radiation effects, *IRS'92*: *Current Problems in Atmospheric Radiation*, Eds. Keevallik, S. and O. Kärner, A. Deepak Publishing, Hampton, Virginia, USA, 47–51, 1993.

Foyo-Moreno I., J. Vida, and L. Alados-Arboledas, Ground-based ultraviolet (290–385 nm) and broadband solar radiation measurements in southeastern Spain, *Int. J. Climatol.*, **18,** 1389–1400, 1998.

Fröhlich, and C. Wehrli, Spectral distribution of solar irradiance from 25000 nm to 250 nm. World Radiation Center, Davos, Switzerland, private communication, 1981.

Gueymard, C., Development and performance assessment of a clear sky spectral radiation model, in *Proc. Solar'93–22nd ASES Conf*, *Washington*, *DC*, 1993.

Gueymard, C., SMARTS2, a simple model of the atmospheric radiative transfer of sunshine: algorithms and performance assessment, *Florida Solar Energy Center FSEC-PF-270-95.*, 78 pp 532, 1995.

Gueymard, C., Turbidity determination from broadband measurements: a detailed multicoefficient approach, *J. Appl. Meteorol.*, **37,** 414–435, 1998.

Horneck, G., Quantification of the biological effectiveness of environmental UV radiation, *J. Photochem. Photobiol. B: Biol.*, **31,** 43–49, 1995.

Iqbal, M., *An introduction to solar radiation*, Academic Press, New York, 390, 1983.

Justus, C. G., and M. V. Paris, A model for solar spectral irradiance and radiance at the bottom and top of cloudless atmosphere, *J. Clim. Appl. Meteorol.*, **24**(3), 193–205, 1985.

Leckner, B., The spectral distribution of solar radiation at the Earth's surface-elements of a model, *Sol. Energy*, **20,** 1431–1450, 1978.

Olmo, F. J., D. Pozo, R. Pareja, and L. Alados-Arboledas, Estimating surface photosynthetically active radiation (PAR) from Meteosat data, *The 1996 Meteorological Satellite Data Users' Conference*. Vienna, 459–463, 1996.

Shettle, E. P., and R. W. Fenn, Models for the aerosol of the lower atmosphere and the effects of humidity variations on their optical properties, AFGL-TR-79-0214-Environmental Res. Paper 676. Hanscom AFL, MA, 1979.

Utrillas, M. P., J. V. Boscá, J. A. Martinez-Lozano, J. Cañada, F. Tena, and J. M. Pinazo, A comparative study of SPCTRAL2 and SMARTS2 parametrised based on spectral irradiance measurements at Valencia, Spain, *Sol. Energy*, **63,** 161–171, 1998.

Varotsos, C., Solar ultraviolet radiation and total ozone, as derived from satellite and ground-based instrumentation, *Geophys. Res. Lett*., **21**(17), 1787–1790, 1994.

Vigroux, E., Contribution a l'étude expérimentale de l'absorption de l'ozone, *Ann. Phys*., **8,** 709–762, 1953.

WMO, *A preliminary cloudless standard atmosphere for radiation computation*. World Climate Programme, WCP-112. WMO/ TD-No 24. World Meteorological Organization, Geneva, Switzerland, 1986.

Won, T., The simulation of hourly global radiation from hourly reported meteorological parameters-Canadian Prairie. *Conference, 3rd, Canadian Solar Energy Society Inc*., Edmonton, Alberta, 1977.